MASS DEPENDENCE OF INTERMEDIATE MASS FRAGMENTS IN MULTIFRAGMENTATION

A thesis submitted in the partial fulfillment of requirement for the award of the degree of

Masters of Science

In

Physics

Submitted by

Bhawna Sharma

Roll no.-300804003

Under the esteemed guidance of

Dr. Suneel Kumar

(Assistant professor)

School of physics and material science

Thapar University

PATIALA (PUNJAB)-147004

July 2010

CERTIFICATE

I hereby declare that the report entitled "**Mass Dependence of Intermediate Mass fragments in Multifragmentation**" is an authentic record of my own work carried out as requirements for the award of degree of M. Sc. (Masters of Science) at Thapar University Patiala (Punjab), under the guidance of Dr. Suneel Kumar (SPMS) during January to July 2010. The matter presented in the thesis has not been submitted in part or full for the award of any other degree.

Bhawna Sharma

Date: 15-7-2010

Bhawna Sharma

Roll No. = 300804003

It is certified that the above statement made by the candidate is correct to best of my knowledge and belief.

S Kumar

(Dr. Suneel Kumar)

Assistant professor,

School of Physics and Material Science,

Thapar University, Patiala,

(Dr. O. P. Pandey)

Professor and Head
School of Physics and Material Science
Thapar University
Patiala

20/7

(Dr. R.K.Sharma)

Dean of acemedic affairs
Thapar university
Patiala

i

dedicated

to

my parents, who offered me
unconditional love

&

my teachers for their support
throughout the course of this thesis

Acknowledgements

I express my deep sense of gratitude and respect to my supervisor ***Dr. Suneel Kumar,*** **Assistant professor, School of Physics and Material Science, Thapar University, Patiala,** for his keen interest and valuable guidance, strong motivation and constant encouragement during the course of this thesis. I thank him from the bottom of my heart for introducing me to nuclear physics. I thank him for his great patience, constructive criticism and myriad useful suggestions apart from invaluable guidance to me. I am sure that the knowledge gained through my association with my supervisor shall go a long way in helping me to realize my goals in life. I would never succeed in my task without cooperation, encouragement and help provided to me by various personalities

I also thank ***Dr. O.P. Pandey***, Professor and Head, School of Physics and Material Science for his support and providing facilities.

A special word of thanks to Mr. Sanjeev Kumar and Mrs. Varinderjit Kaur, Research Scholars for the help and valuable suggestions whenever I needed out of their busy schedule.

My sincere thanks to all the office staff who had made my life easier by providing me assistance in all times of need. I would also like to gratefully acknowledge the support of my classmates. They helped me immensely by giving me encouragement and friendship.

Finally, I would like to express my deepest gratitude to my **parents and family**, without whom I am nothing, to provide me great opportunities, everlasting support, big encouragement and lots of love.

Date: 15-7-2010

Place: Thapar University, Patiala. ***(Ms. Bhawna Sharma)***

Abstract

Nuclear multifragmentation, i.e. observation of many fragment reaction channel is one of the most interesting aspect of the heavy ion collisions. The observation of multifragment configuration would correspond to the state of matter intermediate between nuclear liquid (nucleus close to its ground state) and nuclear vapor (assembly of nucleons and lighter mass fragments at high temperature). The study of nuclear multifragmentation is one of the rare possibilities of studying, microscopically, a phase transition in a finite size fluid. We will study the mass dependence of various quantities (like the average density, collision rate, fragment multiplicity etc. by simulating the reactions at the energy 600MeV/nucleon. This study is carried out within the framework of Isospin dependent Quantum Molecular Dynamics model. We have simulated the reactions $^{197}Au_{79}$+$^{12}C_{6}$, $^{197}Au_{79}$+$^{26}Al_{13}$, ^{197}Au+$^{63}Cu_{29}$ and $^{197}Au_{79}$+$^{208}Pb_{82}$ and collision geometry varied from central to peripheral. Firstly, we will give some details about the experimental, their theoretical scenarios and some of the experimental set ups held in past years in which multifragmentation data obtained. We will also give the theoretical description of the IQMD model. At last we will give qualitative analysis of various results obtained theoretically in multifragmentation and also compare our results with those obtained experimentally from ALADIN experiment.

Table of Contents — Page No.

CHAPTER – 3 MULTIFRAGMENTATION OF $^{197}Au_{79}$ WITH DIFFERENT TARGETS

CHAPTER – 4

List of Figures and tables

Chapter 1

Introduction

1.1 Heavy ion collisions

Heavy ion refers to ionized nuclei which is usually heavier than helium. Heavy-ion physics is devoted to the study of extremely hot nuclear matter and the collective effects appearing in such systems. The branch of physics which deals with the phenomenon when two heavy nuclei brought into contact, such that nuclear forces holding the protons and neutrons within the one nucleus are felt by the other nucleus, is called HEAVY ION PHYSICS. There are number of applications of heavy ion collisions in the field of science and technology.

1.2 Nuclear phase diagram

Let us explain the heavy ion physics with the phase diagram of nuclear matter.

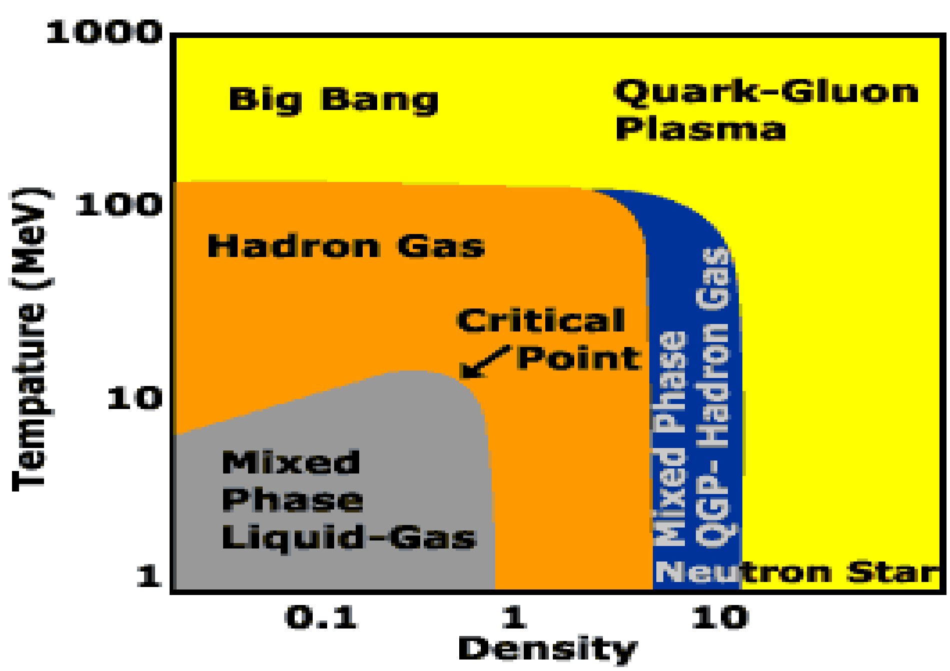

Fig: 1.1: Nuclear phase diagram

What is the purpose of studying the nuclear matter phase diagram? The answer is that we need this information to understand the early history of our universe, and to understand high-density objects, called "neutron stars" in our present-day universe.

One speaks of water existing in three states or phases: solid, liquid, and gas, known to us simply as ice, water, and steam. Temperature and pressure determine the phase of water molecules. Similarly, protons and neutrons exhibit different phases depending on the local nuclear temperature and density. Normal nuclei appear to be in the liquid phase. Different types of nuclear matter include neutron stars, the early universe, a nucleon gas, or quark-gluon plasma. Scientists study these phases by colliding the beams of accelerated particles to produce extreme conditions. At this time, the quark-gluon plasma has not been identified in any experiment. In their normal states of lowest energy, nuclei show liquid-like characteristics and have a density of 0.17 nucleons/fm^3. In a laboratory, the only possible way to heat nuclei to significant temperatures is by colliding them with other nuclei. In atomic physics, the electron-volt ($1.6x10^{-19}$ Joules) is used as a convenient unit. Similarly, nuclear scientists use millions of electron-volts or MeV ($1.6x10^{-13}$ Joules) as a convenient energy unit because it is roughly the energy scale of nuclear processes. An average energy of 1 MeV corresponds to a temperature of $1.2x10^{10}$ K. As we heat nuclei to a temperature of a few MeV, some of the nuclear "liquid" evaporates. Just like water, the nuclear liquid also has a latent heat of vaporization, and nuclei should undergo a first-order phase transition. This liquid-gas coexistence is also expected to terminate at a critical point, the critical point of nuclear matter. We know that thermal equilibrium can be established. Various experiments had been performed to determine at what temperature and density the critical point of nuclear matter is located. Also we do not have the luxury to carefully prepare our sample at a given pressure, temperature and density, as is done when studying the phase diagram of water. Instead we have only a time interval of about 10^{-21} seconds during which we have to conduct our experiment. We also do not have any direct way of measuring the state variables (temperature, pressure, density). We need to determine them from observables such as:

1. the abundance of isotopes,
2. the population of excited nuclear states,
3. the shapes of the energy spectra from nuclear collision remnants
4. the production of particles such as pions

One can view each nucleon as a "bag" containing quarks and gluons. These quarks and gluons can move relatively freely inside their own bag, but "bag" theory says that they cannot escape from the bag–they are "confined". For this reason, we have never been able to detect individual free quarks or gluons. However, if we are able to produce an extremely dense gas of hadrons (mainly pions and nucleons), then their bags can overlap.

This overlap lets the quarks and gluons from different bags to mix freely and travel across the entire nuclear volume. We call this state"quark-gluon plasma,". A region, which is labeled as **Big Bang**, is in the upper left corner of fig: 1.1 in the first microsecond after the Big Bang, the entire universe should have been in this state.

Figure 1.1 also show a region labeled as neutron star. Whenever a massive star undergoes the supernova explosion, a core of iron nuclei remains. Gravity brings the nuclei together. The short-range nuclear repulsive force is not strong enough to keep the nuclei apart. As the core collapses, the individual nucleons separate from the nucleus. The protons become neutrons by inverse beta decay. Therefore, the neutron star is very large collection of neutrons, typically a few kilometers in diameter, which is held together by gravity. Some theoreticians predict that a neutron star of a large enough mass could be of high enough density to produce quark-gluon plasma. This is indicated by the high-density end of the neutron star region.

1.3 Features of Heavy ion collisions

As explained in phase diagram heavy ion collisions offer the study of structure, fission-fusion process, radioactivity and halo nuclei at below the sub normal densities of nuclear matter. The study of heavy ion physics above the normal nuclear matter is quite intense due the existence of extreme conditions like high temperature and high density.

One of the main interests of studying heavy ion reactions is the investigation of the properties of nuclear matter under extreme conditions. The investigations include the production of secondary particles, properties of particles in dense nuclear medium, the compression and repulsion of nuclear matter, its equilibration during the reaction and its decay into fragments and single particles. On a macroscopic level total energy of dense nuclear system and its decomposition into thermal and compressional parts is related to the concept of nuclear equation of state. Heavy ion reactions allow us to search for a large number of observables which may be used as indicators of the properties of nuclear matter under extreme conditions. Frequently these observables are related to the quantitative description of collective effects like bounce-off of cold spectator matter in the reaction plane and squeeze-out of the hot and compressed participant matter perpendicular to the reaction plane as well as production of secondary particles. [1]

1.4 What happens in heavy ion collision

The two nuclei approaching each other, as shown in figure 1.2

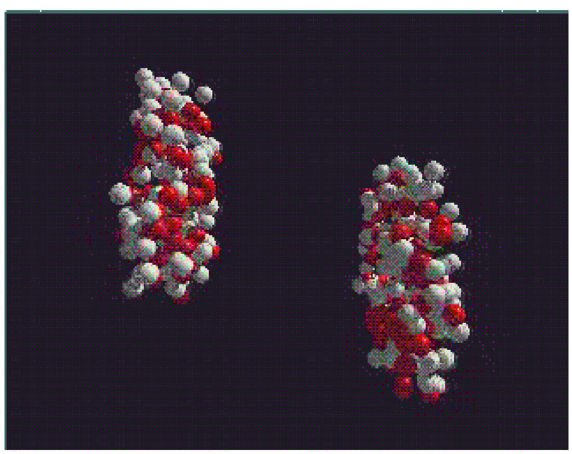

Fig: 1.2: Initialized projectile and target nuclei at time t = 0fm/c

If the nuclei touch, they stop each other and start to build up a hot density region. Kinetic energy is transformed into compressional energy and temperature, as shown in figure 1.3.

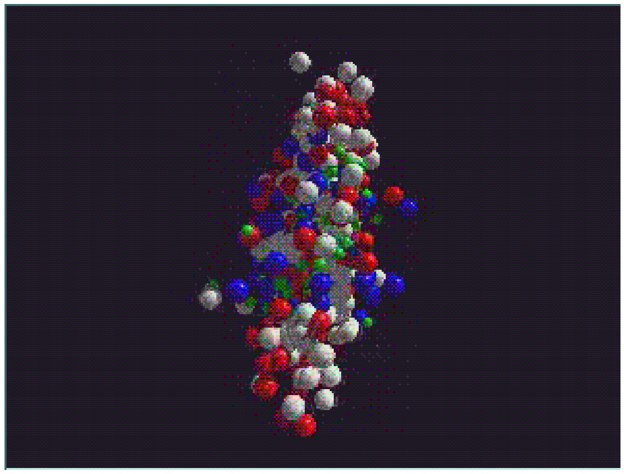

Fig: 1.3: Two nuclei during collision

In this hot region a huge amount of nuclear resonances (blue) are produced. These resonances decay and produce mesons, preferentially pions.

The remnants of projectile and target move off from the compressed region. The hot compressed region itself starts to expand and cool down. The nucleons, resonances and produced mesons perform further interactions (rescattering) which may again produce other forms of resonances and mesons as shown in figure 1.4.

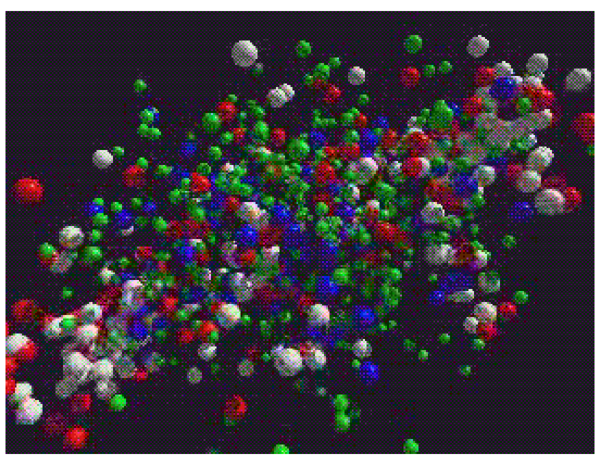

Fig: 1.4: Two nuclei after the collision

The system expands more and more, and the unstable resonances decay.

Heavy ion collisions at intermediate energy are more important, because here we have both mean field as well as N-N collisions. The various types of information's can be extracted from these types of collisions. Heavy ion collisions(HIC) at intermediate and high energies provide a possibility for studying nuclear matter at different conditions as compared to normal nuclei, for example high temperature, high density etc. The nuclear equation of state can be researched via liquid-gas phase transition, multifragmentation, various flows like collective, elliptic etc. produced in heavy ion collisions. [2-4].

1.5 Multifragmentation

A fragment production is most interesting feature of intermediate energy heavy ion reaction, still remains elusive in its interpretation. A heavy ion collision gives the possibility to probe the nuclear matter under different conditions (at different temperature and densities). At high energy the nuclear matter breaks into many fragments, this process is called multifragmentation or we can say when the two colliding nuclei breaks into small and medium fragments also a lots of nucleons are emitted from the participant zone, as shown in the following figure:

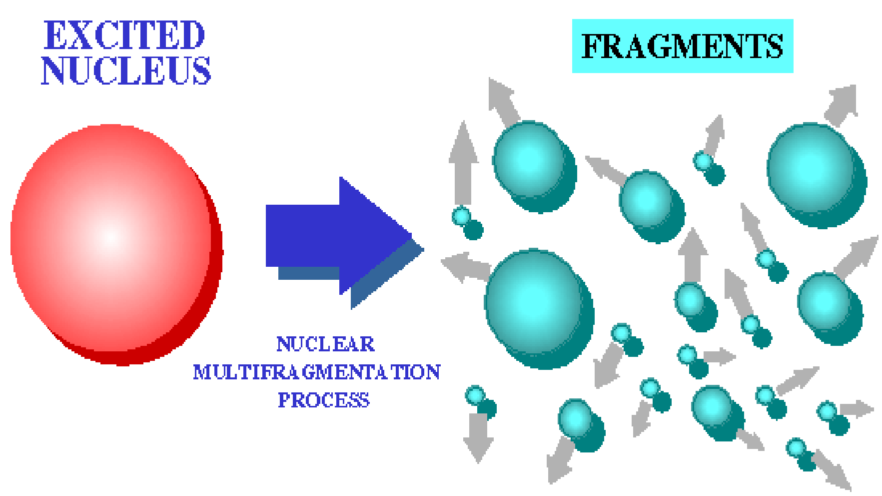

Fig: 1.5: Excited nucleus breaks into the various fragments

The hope to establish a link to the liquid-gas phase transition in the nuclear matter has been the major motivation for the search for and study of multifragment decay of the heavy nuclei in recent years [5-8]. Besides this a lot of work being done in this area there are so many queries related to Multifragmentation, like why do nuclei break into several fragments? How and when they are formed? What is the mechanism behind Multifragmentation? Why does a nucleus shatter into several fragments if hit by a projectile? Is this a statistical process making new micro-canonical phase space models the proper tool for its description or is it dynamical process? Etc. The answers to these queries are given timely making different improvements to the previous findings.

1.6 Equation of State (EOS)

The main goal of heavy ion collisions is to extend the knowledge to hot and dense nuclear matter at extreme conditions. In past years these studies were focuses on the multifragmentation that constituted the fragments of all sizes [9]. Now the question arises, what is equation of state and why it is important? The answer of this question is, equation of state mainly tells us the condition of nuclear matter at different densities and temperatures, in other words it studies the transition of nuclear matter from one phase to another. Multifragmentation is one of the important phenomena in HIC which indicates the EOS at extreme conditions. This is important and useful in the understanding of phenomena like supernova evolution, cooling of neutron stars, etc.

In this thesis, we deal with only one of the aspect, known as multifragmentation, in intermediate energy heavy ion collisions. The literature survey of theoretical and experimental findings is discussed in the coming sections.

1.7 Experimental scenario

Heavy ion collision is a unique way to produce the piece of hot and compressed matter in laboratory, the heavy ion experiments started to nourish the hope that they could serve to determine the equation of state of nuclear matter, i.e. the dependence of the energy per nucleon on temperature and density [10]. In early 50's, one could accelerate the light ions and particles, thus the field was dominated by shooting light particles on heavy targets. As a result, the nuclear physics was confined to the study of phenomena like fusion of two nuclei, fission, exotic emission of clusters, particle transfer etc. At present, one is able to accelerate the nuclei up to several hundreds of GeV and thus, it has opened a new phase of nuclear reactions.

The first experiment at Berkley served mainly to get experimentalists and theoreticians aware of the problems and pitfalls of the medium energy heavy ion collisions and nuclear equation of state. Later on several accelerators are made at Michigan state university (MSU) at USA, GANIL at France and GSI at Germany.

The SIS (heavy ion synchrotron) accelerator at GSI (Germany) is specifically designed to study the heavy ion collisions at intermediate energies. The MSU group at Michigan state university is very active in studying the fragment's spectra at lower side of the bombarding energies. The similar efforts are also made by the INDRA group at GANIL. The ALADIN group at GSI has provided complete spectra of fragments.

The INDRA group at GANIL is studying mainly the collisions where large multiplicity of nucleons is observed in the exit channel. They have undertaken the wide program where influence of different parameters on multifragmentation is studied. In particular size effects are studied in symmetric collisions ^{36}Ar+KCl (at 32, 40, 52, 74MeV/nucleon), ^{58}Ni+^{58}Ni (at 32, 40, 52, 63, 74, 82, 90MeV/nucleon) and ^{238}U+^{238}U (at 24 MeV/nucleon) [11] and ^{129}Xe+^{118}Sn (at 25, 32, 45, 50 MeV/nucleon), ^{181}Ta+^{197}Au (at 33, 39MeV/nucleon) [12] etc. Naturally for studying the gentle compression and Coulomb instabilities, they have to go for heavy fragments.

The Berkley group is mainly concentrated on the asymmetric collisions like $^{197}Au+^{197}Au$, ^{64}Cu, ^{51}V at 60MeV/nucleon [13], $^{36}Ar+^{197}Au$ at 50 and 110MeV/nucleon[14] and $^{56}Fe+^{197}Au$ at 50 and 110 MeV/nucleon [15], $^{139}La+^{12}C$ at 50, 80, 100MeV/nucleon [16] etc. they concentrated on different probabilities which includes excitation energy, angular momentum and velocity distribution.

The FOPI and ALADDIN groups at GSI are studying the variety of reactions giving nearly all kinds of possibilities. It ranges from $^{12}C_6$ to $^{208}Pb_{82}$ and with incident energy between 100 and 1000MeV/nucleon. [17-20].

At present several experimental groups are engaged in extracting information of nuclear EOS from multifragmentation, fragment/nuclear flow. TAPS collaboration recently studied the nuclear incompressibility in the production of hard photons in heavy ion collisions [21]. The new experimental 4π setups at two of the major heavy ion research facilities, GSI (FOPI, KaoS, TAPS) and LBL (TPC) enable the investigation of the emission pattern and correlations of primary and secondary particles in a more detailed manner. It is now possible to investigate thoroughly the phenomenon of correlation such as in-plane bounce off and out-of-plane squeeze out of pions [22].

1.8 Various detectors

There are detectors, which detects the particles or fragments emitted from the reaction zone. Few of them are discussed below:

ALADIN Spectrometer

ALADIN is an electron storage ring operated by the synchrotron radiation center (SRC) of the University of Wisconsin at Madison as a synchrotron light source. 'Aladin' basically a multidetector, used to detect the particles emitted in a reaction. The experimental activity of the Aladin collaboration has predominantly been focuses on the multi fragment decay of the excited spectator nuclei at relativistic bombarding energies. Figure 1.6 represents the schematic apparatus of Aladin multidetector [23].

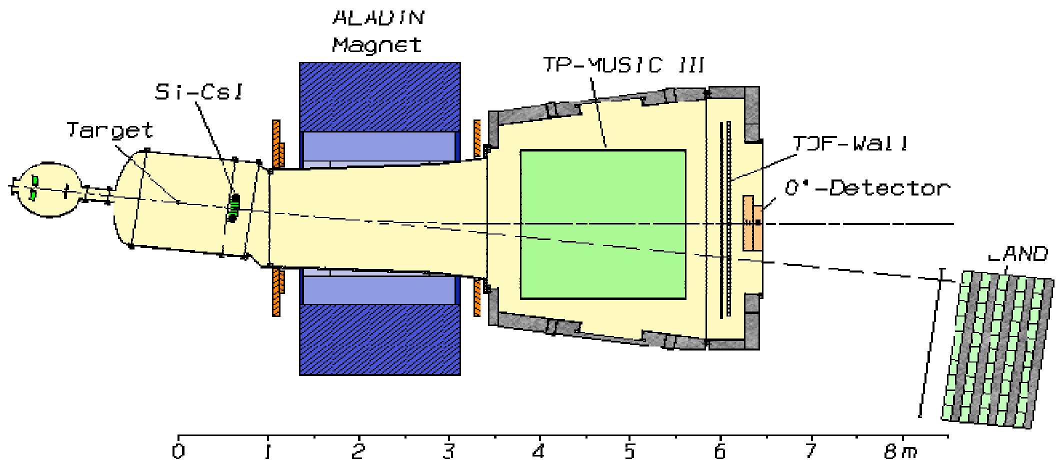

Fig: 1.6. Block diagram of ALADIN Spectrometer

In several experiments with the Aladin spectrometer, the decay of excited projectile spectator matter at the beam energies between 400 to 1000MeV/ nucleons was studied [24-25]. In these collisions, the energy depositions are reached which cover the range from particle evaporation to multi-fragment emission and further to the total disassembly of the nuclear matter, the so-called 'rise and fall of fragment emission'.

FOPI (4π)-Detector

The FOPI detector has documented the investigation of the fragments and the particles produced in central heavy-ion collisions. As suggested by the name - FOPI stands for 4π; a synonym for the entire solid angle-this detector detects, identifies, and determines the momentum of all charged particles emitted in a heavy ion collision. The detector structure is shown schematically in the fig. 1.7.

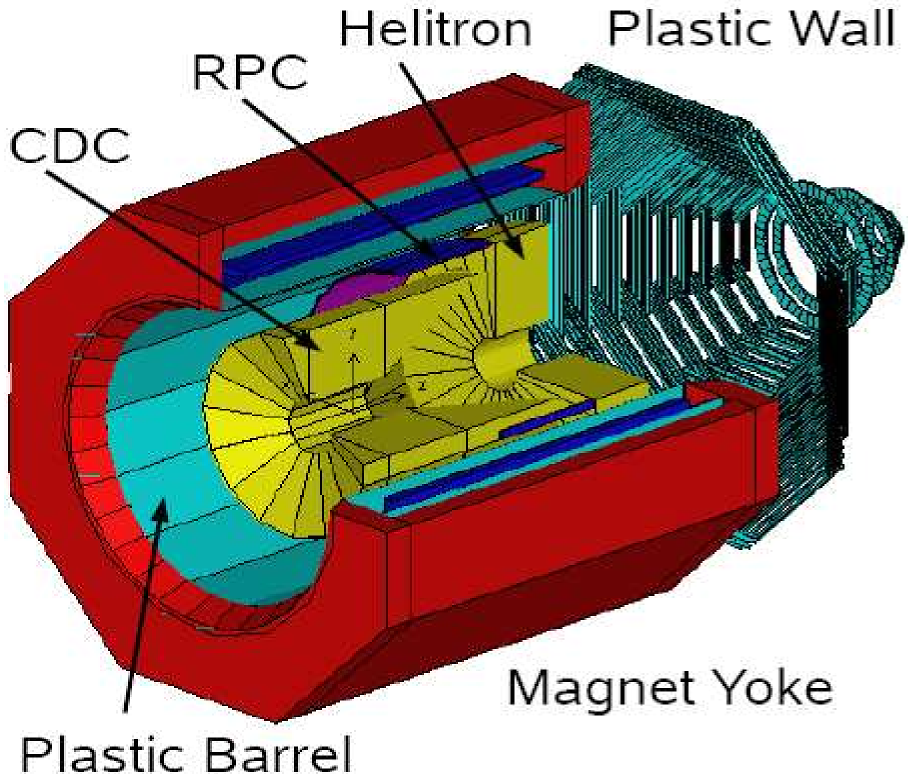

Fig: 1.7: Experimental set up of FOPI apparatus

The FOPI apparatus was designed to study heavy ion reaction in the energy range 0.1-2 GeV/A. The target is located within a superconducting coil, which produces a magnetic field of 0.6 Tesla. The charged particles within this field travel along curved paths before passing through the drift chambers. The drift chambers are CDC (central drift chamber) and HELITRON. Particle analysis is done by combined energy loss, time of flight and magnetic rigidity analysis.

The chambers register both the particle track and the energy loss sustained by the particle in its passage through the detector gas. The energy loss is dependent on the type of particle and its momentum in a characteristic way. Time of flight and energy loss is determined by about 1000 scinillator detector arranged octagon ally in the downstream part of detector (Plastic Wall) and as a barrel inside the magnet. At lower energies(<400MeV/A) a set of gas ionization chambers are inserted in front of Plastic Wall to allow identification of slower heavy clusters.

Inside the magnet the particles are tracked in drift chambers, the central drift chamber, (CDC) and HELITRON as shown in the figure [26]. The figure 1.7 allows us to visualize individual particle tracks in a particular event with the use of local or global track finding methods. By matching these tracks to the outer barrel scintillator, we can obtain the energy loss, track of curvature and time of flight.

Minibal detector

German, Belgian and French physicists have developed a γ-detector array called Minibal. The Minibal array has eight cluster detectors and each cluster consists of three individually encapsulated six-fold segmented high purity germanium detectors. In the Minibal array the new technology of encapsulated germanium detectors is used, where each detector module is kept under UHV vacuum in a thin-walled aluminium cane. The advantage is that the single detectors of a cluster can be replaced easily in the common dewar. Thus the malfunction of an individual detector does not influence the remaining cluster. The importance of this technology increases with the number of energy signals from a sub-unit. Furthermore, the annealing of detectors is simplified. Fig: 1.8 shows the experimental set up of Minibal detector.

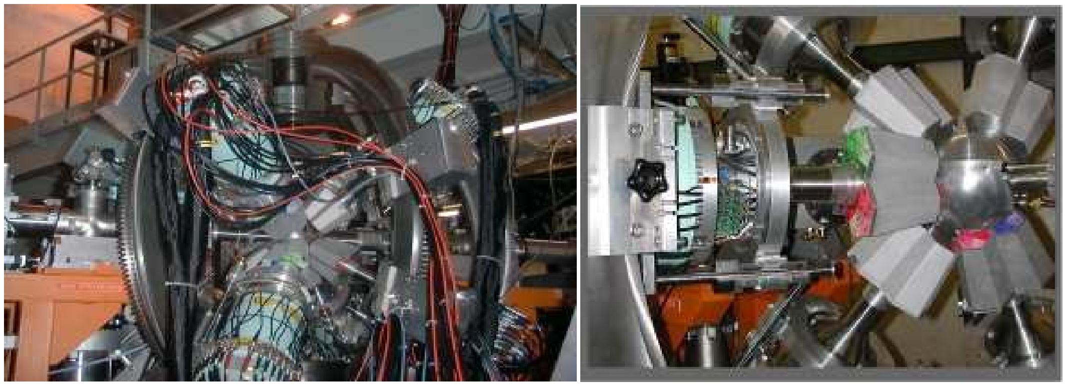

Fig: 1.8: Experimental set up of Minibal Detector

This new technology of encapsulated germanium detectors and their combination in cluster detectors has been proposed and realized in the framework of the Euroball project. This is used for low multiplicity experiments.

1.9 Theoretical scenario

Heavy-ion collisions involve very complicated non-equilibrium physics; therefore, its numerical modeling is not straight forward. As two heavy nuclei approach each other in a collision, they form a highly-correlated strongly-interacting finite quantum system. As they collide and the beam energy is distributed, the participant nucleons reach higher energy levels where the Pauli principle is less restrictive on the energy transfer. At this point the nuclear Fermi-gas begins to resemble a more classical one, and thus one is allowed to speak of temperature and phase transitions in the classical sense. Since the collision can be divided into, say, three stages, collision/compression, expansion/breakup, and cooling. Therefore when a phase transition takes place, the system expands and disassembles into clusters (liquid droplets and gaseous particles), which continue de-exciting by further fission and photon particle emission. Theoretically, several models have been developed which make the situation more complicated. These models can be broadly divided into dynamical and statistical models, with some hybrid approaches linking these two extremes.

Dynamical Models: Some of dynamical models are using 1-body approaches like BUU/BNV/Landau-Vlasov transport theory. However, N-body approaches have also been developed, such as the QMD/AMD/FMD/IQMD. The N-body approaches are very powerful in the description of the simultaneous break-up of a nuclear system in multiple fragments, since they preserve correlations among nucleons [27].

Statistical Models: These models used to study an equilibrated excited source at thermal equilibrium (freeze-out). The most widespread statistical model is SMM [28-29] and its modifications ISMM [30] and TF-SMM [31].

In the following we have discussed various theoretical methods, which are used in the study of heavy ion collisions.

Time dependent Hartree-Fock (TDHF): The time dependent Hartree-Fock (TDHF) [10, 32] or its semi-classical version the so called Vlasov equation (in phase-space) is suitable approaches at low energies where the nucleon-nucleon collisions are negligible. Some attempts were made in the literature to extend the TDHF to take care of the residual nucleon-nucleon (NN) interactions which are responsible for two body collisions (this was dubbed as ETDHF)[33]. However due to complications, this theory could not be used for large scale investigations.

Intra nuclear cascade (INC): The intra nuclear cascade (INC) theoretical approach was a great success for many years and is still widely used as a rough model of the nuclear collision. At intermediate energies, the mean field and two body nucleon-nucleon collisions play an equally important role in the evolution of the system. In this model the mean field is totally neglected and the nucleon-nucleon (NN) collisions are taken without Pauli-blocking [34-35]. The basic INC idea is to view the interaction as a sequence of two-body collisions between the particles involved. The Cascade model simulates the heavy-ion collisions as a superposition of independent two body NN collisions. Naturally, in the absence of mean field, the nucleons move on straight line trajectories until they collide.

<u>Boltzmann Uhenling Uhlenbeck (BUU):</u> In the BUU model, the heavy ion collision is described by the temporal evolution of the one-body density within mean field. This mean field is usually taken as that produced by the motion of the nucleons averaged over an ensemble of configurations. Other related approaches are the Vlasov-Uhenling-Uhlenbeck (VUU) and the Boltzmann-Langevin methods [36].

<u>Isospin dependent Boltzmann Uhenling Uhlenbeck (IBUU)</u>: The IBUU transport used in the present study treats explicitly protons and neutrons. It also includes an asymmetry term in the nuclear mean-field potential and different scattering cross sections for protons and neutrons [37].

<u>Molecular Dynamics</u>: The classical molecular dynamics (MD) approach [38] (or the equation of motion), in principle, is capable of treating both the compression and the fragment formation. The molecular dynamics predicts the collective (sideward's) flow in a qualitative agreement with the data. It incorporates the complete classical N-body dynamics which is necessary to describe the formation of the fragments. In nuclear physics, the key problem in MD methods lies in the treatment of the Pauli principle. As nucleons are fermions and it is difficult to speak of nuclei without the Pauli principle. With the passage of time QMD model is developed by taking case of the quantum features like Pauli blocking, Fermi momentum and deep inelastic scattering. Its isospin dependent version known as Isospin dependent QMD is very successful in explaining the isospin effects in heavy ion collisions by treating the protons and neutrons explicitly.

The QMD and IQMD models are discussed in detail in the next chapter.

However in past years many active programs have been developed at many places. There are many research groups working on IQMD model at international level which includes the Centre of Theoretical Nuclear Physics, National Laboratory of Heavy ion Accelerator Lanzhou(China) CCAST (World Laboratory), Beijing and Lawrence Berkley National Laboratory at University of California[39-40].

1.10 Objective of work

In the present work we have made an attempt to study the multi-fragment production of projectile spectator for different targets. Our analysis carried by using Isospin dependent Quantum Molecular Dynamics (IQMD) model. We simulated the thousand events for the systems $^{197}Au_{79}+^{12}C_{6}$, $^{197}Au_{79}+^{26}Al_{13}$, $^{197}Au_{79}+^{63}Cu_{29}$ and $^{197}Au_{79}+^{208}Pb_{82}$, here the projectile is fixed. Simulations were carried out for various impact parameters and using hard and soft equation of state. The collision geometry varied from central to non-central from $\hat{b}$ = 0 to 1

Motive of our work is to compare the theoretical findings with the available experimental results in intermediate heavy ion collisions. Experimental data is available for Intermediate mass fragments for different targets, impact parameters and energies produced by ALADIN Collaboration Experiments. In the following, we perform the same work for the system $^{197}Au+^{12}C_{6}$, $^{197}Au+^{26}Al_{13}$, $^{197}Au+^{63}Cu_{29}$ and $^{197}Au+^{208}Pb_{82}$ heavy ion collisions.

References

[1] Ch. Hartnack, Rajiv K Puri, J. Aichelin, J Konopka, S.A.Bass, H.Stocker, W. Greiner, Eur Phys. J. A 1 **151** 169 (1998).

[2] W.Cassing, V Metag, U Mosel and K.Naiita, Phys. Rep. **188** 363 (1990).

[3] J Harris and B Muller, Ann. Rev. Nucl. Part. Sci **46** 71 (1996).

[4] C. M Ko and G Q Li, J Phys. Nucl. Part. Phys. **22** (1673).

C. M Ko, G Q Li and V. koch Ann. Rev. Nucl. Part. Sci **47** 509 (1997).

[5] C. A. Ogilvie et al., Phys. Rev. Lett**. 67**,1214 (1991).

[6] W. Trautmann, nucl-ex/9611002, (1996).

[7] P. J. Siemans, Nature (London) **305**, 410 (1983).

[8] J. Hufner, Phys. Rep. **125**, 129 (1985).

[9] J. Singh, S. Kumar, R. K. Puri, Phys. Rev. **C 62** 044617 (2000); **63**, 054603 (2001); A Le, Fevre and J. Aichelin, Phys. Rev. Lett. **C 100**, 042701 (2008); Y. K. Vermani, R. K. Puri, Eur. Phys. Lett. **85**, 62001, (2009); S. Kumar, S. Kumar and R. K. Puri, Phys. Rev. **C 78**, 064602 (2008).

[10] H. Stoker and W. Greiner, Phys. Rep. **137**, 277 (1986).

[11] Ch.O.Bacri et al.,Int. Workshop on multiparticle correlations and nuclear reactions, Nantea, France, p.**388** (1994).

[12] J. Lukasik et al., Phys. Rev. **C 55** 1906 (1997).

[13] L. G. Moretto, D.N. Delis, G. J. Wozaik, Phys. Rev. Lett. **71**, 3935 (1993).

[14] L. Phair et al., Phys Rev Lett. 75, 213 (1995) ; . Phair et al., Phys Rev Lett. **77**, 822 (1996).

[15] T. C. Sangter et al., Phys. Rev. **C 46**, 1404 (1992).

[16] D. R. Brown et al., Nucl. Phys. **A 523**, 383 (1991).

[17] J. P Alard et al., Phys. Rev. Lett.**69**, 889(1992).

[18] G. Poggy et al., Nucl. Phys. **A 586**, 755 (1995).

[19] J. P. Hubbele et al., Z. Phys **A 340**, 263 (1991).

[20] M. Begemann Blaich et al., Phys. Rev. **C 48**, 610 (1993).

[21] Yevz Suhutz and TAPS Collaboration, Nucl. Phys. **A 599**, 97 (1996).

[22] C. Hartnack , S.A.Bass, H.Stocker, W. Greiner. Phys. Rev. Lett. **71**, 1144 (1993).

[23] K. D. Jacobs, J. J. Bisognano, R. A. Bosch, D. E. EIsert, M. V. Fisher, M.A. Green R. G. Keil, K.J. Kelmann, R. A. Legg, G. C. Rogers and J.P. Stott, Synchrotron Radiation Center, University of Wisconsin at Madison, 3731 Schneider, Dr. Stonghton. WI 53589, USA.

[24] J. Hubble, et al., Z. Phys**.** **A 340**, 263 (1991).

[25] J. Hubble, Nucl. Phys. **A 556**, 672 (1993).

[26] R.W. Minich et al., Phys. Lett. **B 118**, 458 (1982).

[27] A. Ferrari, M.V. Garzelli, P.R. Sala, nucl-ex/0910.3416v1, (2009).

[28] A.S. Botvina *et al*. Nucl. Phys. *A* **475,** 663 (1987).

[29] S. Das Gupta and A.Z. Mekjian, *Phys. Rev.* ***C*** **57,** 1361 (1998).

[30] W.P. Tan et al., Phys. Rev. **C 68,** 034609 (2003).

[31] S.R. Souza et al., Phys. Rev. **C 79,** 054602 (2009).

[32] K. T. R. Davies and S. E. Koonin, Ann. Of Phys. Rev. **C 23**, 2042 (1981).

[33] E. Suraud, Ch. Gregoire and B. Tamain, Prog. Part. Nucl. Phys. **23**, 357 (1989).

[34] S. D. Gupta, C. Gale and J. Gallego, Phys. Rev. **C 33**, 1634 (1986).

[35] G. Bertsch and J. Cugnon, Phys. Rev. **C 24**, 2514 (1981).

[36] J. Cugnon, Phys. Rev. **C 22**, 1885 (1980).

[37] B. A Li and S. J. Yennello, Phys. Rev. **C 32** R1746 (1995).

[38] A. R. Bodmer, C.N. Panos and A. D. Mackellar, Phys. Rev. **C 22**, 1025 (1980); L.Wilets, Y. Yariv and R. Chestnut, Nucl. Phys. **A 301**, 359 (1970).

[39] C. Hartnack, Ph.D Thesis University of FrankFurt, Germany (1989).

[40] H. Stocker, L. P. Csernai, G. Buchwala, H. Kruse, R.Y. Cusson and W. Greiner, Phys. Rev. **C 215**, 1873 (1982).

Chapter 2

Methodology

2.1 Introduction

The information about the nuclear equation of state is still a burning topic of present-day nuclear physics research in general and of research of heavy ion collisions in particular. Quite good progress has been made in recent years in determining the nuclear equation of state from heavy ion collisions [1-3]. One of the main goals of HIC is to investigate the real and imaginary part of nuclear heavy ion reaction. The study of heavy ion collisions at intermediate energy needs the correct treatment of real and imaginary parts of nuclear interactions. The read part deals with the trajectory of nucleons whereas imaginary part influences the nucleon-nucleon collisions. In the following we will discuss some of the models:

2.2 Quantum molecular dynamics model (QMD)

The QMD model is a N-body theory which simulates heavy ion reaction at intermediate energies on an event by event basis. Here each event is simulated independent of other. Quantum molecular dynamics (QMD) model contains two dynamical ingredients, the density dependent mean field and the in-medium nucleon-nucleon cross-section. In this model each nucleon is represented by a coherent state and has Gaussian-shaped density distribution. The model mainly consist three steps, which are as following:

1. Initialization
2. Propagation
3. Collision

Firstly we have to generate the nuclei, this procedure is called initialization. These nucleons then propagate under the influence of surrounding mean field. This is termed propagation. Finally the nucleons are bound to collide if they come too close to each other; this part is called as collision [4].

In order to explain experimental results much better, the original version of QMD was modified to include isospin degree of freedom explicitly and the isospin dependence as for the coulomb potential, symmetry potential, N-N cross-sections and Pauli blocking, which is known as Isospin Quantum molecular dynamics model (IQMD).

2.3 Isospin dependent Quantum molecular dynamics model (IQMD)

The IQMD model has been successfully used for the analysis of large number of observables and from low to high energies. It treats different charge states of nucleons, pions and deltas explicitly as inherited from Vlasov-Uehling Uhlenbeck (VUU) model [5,6]. The isospin degree of freedom enters into the calculations via symmetry potential, cross sections and coulomb interaction [7]. As it is developed from VUU model, so it's coding in independent of original QMD.

Initialization in IQMD

In this model the nucleons are represented by the Gaussian-shaped density distributions. Here the centroids of the Gaussians in the nucleus are randomly distributed in a phase space sphere ($r \leq R$ and $P \leq P_F$) with $R = 1.12A^{1/3}$ fermi corresponding to the ground state density $\rho_0 = 0.17 fm^{-3}$. The Fermi momentum depends on the ground state density. For $\rho_0 = 0.17 fm^{-3}$ the value of $P_F \approx 2.68 MeV/c$. due to this collision the nucleus lose to the surface (where the local potential energy is low) are unbounded initially. As a result binding energy is low as compared to the Weizsacker mass formula; hence the initialized nuclei are less stable against spurious particle evaporation as compared to QMD model. Finally it should be noted that IQMD performs a Lorentz contraction of the nucleus coordinate distribution which is not present in QMD and also important for higher energies [8].

Interaction range

Gaussian width is regarded as a description of the interaction range of a particle. Its influence disappears at infinite nuclear matter whereas for finite systems it plays an important role. It is denoted by L.

In IQMD the Gaussian width can be used as an optional input parameter. The system dependence of L In IQMD has been introduced in order to obtain maximum stability of the nucleonic density profiles. As an example for Au+Au a value of L=8.66fm^2 is chosen, for Ca+Ca and lighter system L=4.33fm^2.

Pauli Blocking

The consideration of Pauli blocking effect is very important. Whenever a collision has occurred, in the phase space we assume that each nucleon occupies a six dimensional sphere with a volume of $h^3/2$ (considering the spin degree of freedom), and then calculate the phase volume, V, of the scattered nucleons being occupied by the rest nucleons with the same isospin as that of the scattered ones. We then compare $2V/h^3$ with a random number and decide whether the collision is blocked or not. Therefore, the Pauli blocking is isospin dependent, namely, the Pauli blocking of neutrons and protons is treated separately. In addition, Pauli blocking (of the final state) of nucleons is taken into account by checking the phase space densities in the final states [9].

The final phase space fractions P_1 and P_2, which are already occupied by other nucleons, are determined for each of the scattering nucleons. The collision is then blocked with probability

$$P_{block} = 1 - (1 - P_1)(1 - P_2). \qquad (2.1)$$

Propagation

In this model nucleons are represented by the Gaussian-shaped density distributions:

$$f_i(\vec{r},\vec{p}),t = \frac{1}{(\pi\hbar)^3} \times e^{[-(\vec{r}-\vec{r}_i\,(t)\,)^2 \frac{2}{L}]} \times e^{[-(\vec{p}-\vec{p}_i\,(t)\,)^2 \frac{L}{2\hbar^2}]} \qquad (2.2)$$

The nuclei which are successfully initialized are boasted towards each other with a proper centre of mass velocity using relativistic kinematics. The particles are propagated under the total interaction calculated by the Hamiltonian equations of motion:

$$\frac{dr_i}{dt} = \frac{d\langle H\rangle}{dp_i}, \qquad \frac{dp_i}{dt} = -\frac{d\langle H\rangle}{dr_i} \tag{2.3}$$

The Hamiltonian function $\langle H\rangle$ contains all the possible interactions of the particles of the system. The total Weigner density is therefore, sum of all nucleons. The expectation value of the Hamiltonian is

$$\langle H\rangle = \langle V\rangle + \langle T\rangle$$

$$= \sum_i \sum_{j>i} \int f_i(\vec{r},\vec{p},t) V^{ij}\left(\vec{r'},\vec{r}\right) \times f_j(\vec{r'},\vec{p'},t)\, d\vec{r}\, d\vec{r}'\, d\vec{p}\, d\vec{p}' \tag{2.4}$$

The baryon-baryon potential V^{ij} consists of real part of Bruckner G-matrix which is supplemented by effective coulomb interaction which is acting between charged particles. The former part can be parameterized by the skyrme type interaction to finite Yukawa potential as well as momentum dependent contribution [10].

In addition to symmetry potential between protons and neutrons corresponding to Bethe-Weizsacker mass formula has been included. Therefore V^{ij} consist of:

$$V^{ij} = G^{ij} + V^{ij}_{Coul}$$

$$= V^{ij}_{Skyrme} + V^{ij}_{Yukawa} + V^{ij}_{mdi} + V^{ij}_{Coul} + V^{ij}_{sym}$$

$$= t_1\delta(\vec{x}_i - \vec{x}_j) + t_2\delta(\vec{x}_i - \vec{x}_j)\rho^{\gamma-1}(\vec{x}_i) + t_3\frac{\exp\left(\frac{|\vec{x}_i - \vec{x}_j|}{\mu}\right)}{\frac{|\vec{x}_i - \vec{x}_j|}{\mu}} +$$

$$t_4 \ln^2(1 + t_5(\vec{\rho}_i - \vec{\rho}_j)^2)\,\delta(\vec{x}_i - \vec{x}_j) + \frac{Z_i Z_j e^2}{|\vec{x}_i - \vec{x}_j|} + t_6\frac{1}{\rho_0}T^i_3\, T^j_3(\vec{r}_i - \vec{r}_j) \tag{2.5}$$

In the description of the coulomb interaction V^{ij}_{Coul}, Z_i, Z_j are the charges of i^{th} and j^{th} baryons. The parameters $t_1...t_5$ are uniquely related to the corresponding values of α, β, γ, δ and ε which serve as input. In the calculations presented in this article the parameterization SM is used as standard. It is a combination of Skyrme type and momentum dependent potential with a low compressibility. Parameters used in above equation 2.5 are given in table 2.1.

IQMD Parameters	
t_3	15 MeV
t_4	1.57 MeV
t_5	5.10^{-4} MeV^{-2}
t_6	25 MeV
μ	0.4fm

Table .2.1: IQMD parameters used in equation 2.5

The momentum dependent V^{ij}_{mdi} of the NN interaction which may optionally be used in the model, is obtained from a fit to the experimental data [11-12] on the real part of nucleon optical potential which yields.

$$V^{ij}_{mdi} = \delta . ln^2(\varepsilon .(\Delta\vec{p})^2 + 1). \frac{\rho_{int}}{\rho_0} \qquad (2.6)$$

The IQMD model offers rather stable density distributions and good energy conservation, however for the price of nucleons evaporation and improper binding energies (E_{bind}=4-5MeV/nucleon for heavy nuclei instead of 8MeV/nucleon).

In addition to the use of the explicit charge states of all baryons and mesons a symmetry potential between protons and neutrons corresponding to the Bethe-Weizsacker mass formula has been included. The symmetry energy term is given by

$$V^{ij}_{sym} = t_6 \frac{1}{\rho_0} T^i_3 \, T^j_3 \delta(\vec{r}_i, \vec{r}_j) \quad (2.7)$$

Where T^i_3 and T^j_3 denote the isospin T_3 of i^{th} and j^{th} particles, i.e. ½ for protons and -1/2 for neutrons . The constant t_6 = 100 MeV. From the above equations, one can see that the nuclear mean field is isospin dependent in the IQMD model.

Collision

The scattering of nucleons in nuclear matter in low density expansion can be described in terms of reaction G-matrix. At high energies the influence of Pauli blocking is less and kinetic energy is large as compare to the potential. Then the imaginary part of the reaction matrix becomes identical to the transition matrix which describes the scattering between two nucleons [13]. Scattering can be elastic or inelastic. Two particles collide if their minimum distance r, i.e. the minimum relative distance of the centroids of the Gaussians during their motion, in their CM frame fulfills the requirement:

$$\left|\vec{r}_i - \vec{r}_j\right| \leq \sqrt{\frac{\sigma_{tot}}{\pi}}, \qquad \sigma_{tot} = \sigma(\sqrt{s}, type) \quad (2.8)$$

Where "type" denotes the ingoing collision partners (N −N, N − Δ, N − π etc.)
The colliding particles can also scatter elastically or inelastically. This processes include:

$$\text{Elastic: } \begin{cases} N + N \rightarrow N + N \\ \Delta + \Delta \rightarrow \Delta + \Delta \\ N + \Delta \rightarrow N + \Delta \end{cases} \quad (2.9)$$

$$\text{Inelastic: } \begin{cases} N + \Delta \rightarrow N + N \\ N + N \rightarrow N + \Delta \end{cases} \quad (2.10)$$

σ_{tot} is the total cross-section i.e. sum of elastic and inelastic cross sections:

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} \quad (2.11)$$

Scattering angles of single N-N collisions are randomly chosen such that sum of the scattering angles of all the collisions agrees with the measured angular distribution for elastic collisions. However inelastic collisions lead to the formation of deltas which can be reabsorbed by the inverse reaction.

2.4 MST (Minimum Spanning Tree) Method

The minimum spanning tree method (MST) [3,14-20] is used in cluster analysis and track finding, if we consider tracks to be cluster of points. In MST, to nucleons share the same fragment if their centroids are closer than a distance d_{min},

$$\left|\vec{r}_i - \vec{r}_j\right| \leq d_{min} \quad (2.12)$$

Where r_i and r_j are the spatial positions of both nucleons. The minimum distance d_{min} has been used as a free-parameter which varies between 2-4fm. Its influence on multifragmentation (at 200-300fm/c) is reported to be small [21]. This approach (being a spatial distance approach) cannot deflect different fragments which are (almost) overlapping and therefore, will give a single big fragment during the early stage of reaction where density is quite high and the interactions among nucleons are still active. One simulates the reaction using IQMD. Then spatial distance of all nucleons is checked. A nucleon is a part of fragment if there is another one within a distance of r_{min}=4fm. This method is also called Spatial Correlation Method. However there are several methods which are used for cluster analysis, SACA (Simulating Annealing Clusterization Algorithm) is one of them.

References

[1] Suneel kumar, Sanjeev kumar and Rajiv. K. Puri. Phys. Rev. **C 81**, 014611 (2010).

[2] P.Danielewicz, R.Lacey and W. G. Lynch, science **298**, 1592 (2002); H. Stocker and W. Greneir, Phys. Rep **137**,273 (1986); W. Reisdrof and H.G. Ritter, Annu. Rev. Nucl. Sci. **47**, 663 (1997); C. Hartnack and J. Aichelin Phys. Rev. C **49**, 2801 (1994); S. Kumar, S.Kumar and R. K. Puri ibid **78**, 064602 (2008); A. R. Raduta and F.Gulminelli, ibid 75, 024605 (2007).

[3] J. Aichelin Phys. Rep. **202**, 233 (1991).

[4] Suneel Kumar, Ph.D. Thesis, P.U. Chandigarh (1999).

[5] C. Hartnack. Ph.D Thesis, GSI-Report 93-5 (1993).

[6] C. Hartnack, L. Zhuxia, L. Neise, G. Peilert, A. Rosenhauer, H. Sorge, J. Aichelin, H. Stocker and W. Greiner, Nucl. Phys. **A 495** 303 (1989).

[7] H. Kruse, B.V. Jacak, H. Stocker, Phys Rev. Lett. 54, 289 (1995); J.J. Motalorias Phys Rev **C 32**, 346(R).

[8] Ch. Hartnack, Rajiv K Puri, J Aichelin, J Konopka, S.A.Bass, H.Stocker, W. Greiner, Eur Phys. J. A 1 **151** 169 (1998).

[9] Chen Liewen, Zhang Fengshou, and Jin Genming Phys. Rev. **C 58,** 2283 (1998).

[10] Suneel kumar, Sanjeev kumar and Rajiv. K. Puri. Phys. Rev. **C 81**, 014601 (2010).

[11] L. G. Arnold et al., Phys. Rev. C **25**, 936 (1982).

[12] G.Passatore, Nucl. Phys. A **95**, 694 (1967).

[13] G. Peilert, A. Rosenhauer, H. Stocker ,W. Greiner, A. Bohnet, J. Aichelin Phys. Rev. **C 37**, 2451 (1988).

[14] A. Bohnet, N. Ohtsuka, J. Aichelin, R. Linden and A. Faessler, Nucl Phys. **A 494**, 349 (1989).

[15] D. T. Khoa, N. Ohtsuka, A. Faessler, M.A. Matin, S.W. Haung, E. Lehmann and Y. Iofty, Nucl. Phys. **A 542**, 671 (1992).

[16] R. K. Puri and S. Kumar Phys. Rev **C 57**, 2744 (1998).

[17] S. Kumar and R. K. Puri Phys. Rev **C 58**, 320 (1998).

[18] R. K. Puri and S. Kumar Phys. Rev **C 58**, 2858 (1998).

[19] C. A. Ogilvie et al., Phys. Rev. Lett. **67**, 1214 (1991).

[20] M. Begemann Blaich et al., Phys Rev **C 48**, 610 (1993).

[21] G. Peilert, M. Blann, H. Stocker, W. Greiner, J. Konopka and M. G. Mustafa, Phys. Rev. **C 46**, 1457 (1992).

Chapter 3

Multifragmentation of Au^{197} with different targets

3.1 Introduction

It is now well established that highly energetic system formed during nucleus-nucleus collisions can decay into several intermediate and lighter mass fragments. In simpler words one can say that the breaking of nuclear matter is known as multifragmentation. At low incident energies, fusion is more probable whereas at high incident energies multifragmentation dominates. In the preceding chapters, a detailed picture of multifragmentation in heavy ion collisions is presented.

Fig. 3.1 shows a picture of heavy ion collision. Here the two nuclei approaching each other at non central impact parameter. The nucleons which undergo collisions are called participants or participant zone of reaction and which does not undergo any collision called spectators.

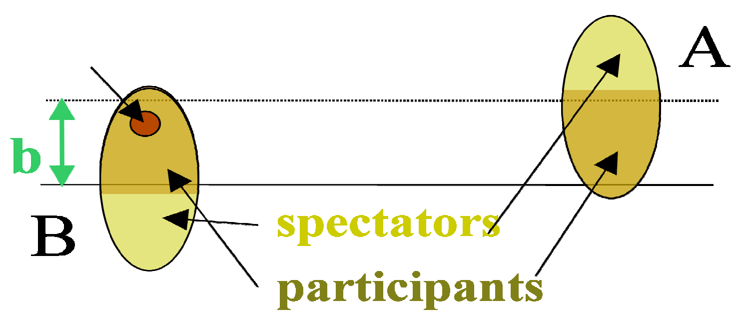

Fig: 3.1.Schematic diagram of heavy Ion Collision

3.2 Multifragmentation of heavy projectile with lighter targets

The multifragment decay of heavy projectile with lighter targets mainly focus on the projectile spectator decay, this type of experiments are performed by the Aladin Collaborations at various energies [1-4]. The most prominent feature of mutli-fragment decay is universality is obeyed by fragment multiplicities and fragment charge correlations. These observables are invariant with respect to the entrance channel i.e independent of beam energies and targets if plotted against Z_{bound} (sum of all atomic numbers of projectile fragments with $Z \geq 2$). For the different projectiles, the dependence of fragment multiplicity on Z_{bound} follows the linear scaling law [1].

There are various experiments performed by different groups like INDRA, FOPI, ALLADIN, TAPS Collaborations [5-6] etc. at different incident energies. These experimental studies of the multifragmentation with sophisticated instruments have revealed several phenomena: Ogilvie et al. [7] have shown that there is rise and fall in multifragment production with a change in impact parameter. The analysis of various experiments has showed that the rise and fall in multiplicity of fragments (as a function of impact parameter) occurs only if the energy is above 250MeV/nucleon. The mean multiplicity, however decreases monotonically at energy 100MeV/nucleon. It has been established that IMF production is strongly affected by the change in incident energy and impact parameter. If one increases the energy beyond 400MeV/nucleon, no change in IMF production is reported by the ALADIN group [2]. These experiments were performed by heavy projectiles and targets like Au. A similar behavior of fragment production is also observed in the collision of lighter nuclei like, Ca, Nb, Kr, Xe, etc. [8-9]

3.3 Results and Discussion

For the present study, we have simulated the collisions between Au projectile and C, Al, Cu and Pb as targets using IQMD (isospin dependent quantum molecular dynamics) model at incident energies 600MeV/A. The collision geometry changed from central to peripheral. The phase space obtained by IQMD is analyzed by Minimum spanning tree method (MST) [10]. The results obtained are discussed in the following sections:

3.4 Time evolution of rate of N-N collisions

The final form of nuclear matter is closely related to the density of collision. We define the average nuclear density as

$$\langle \rho(\mathrm{r_i}) \rangle = \langle \sum_{j=0}^{n} \frac{1}{(2\pi L)^{3/2}} e^{-(\vec{\mathrm{r}}_\mathrm{i}-\vec{\mathrm{r}}_\mathrm{j})^2/2\mathrm{L}} \rangle$$

The above density definition shows the number of nucleons in the vicinity of each nucleon. Fig.3.2 and shows the variation of allowed collisions with respect to time for the four different reactions at energy 600MeV/nucleon. Here we consider the case of central collisions only and similar types of curves are obtained for the time evolution of density (not shown here). We noticed that density is closely related to the rate of collisions.

As is observed from the figure that scenario is different at during the compression stage and saturation stage. During the compression stage, the rate collision is minimum for highly asymmetric system i.e. $^{197}Au_{79}$+$^{12}C_6$, while it goes on increasing with decrease in asymmetry of the system from $^{97}Au_{79}$+$^{26}Al_{13}$ to ^{197}Au+$^{63}Cu_{29}$ followed by $^{197}Au_{79}$+$^{208}Pb_{82}$. This is due to the effect that with the decrease in asymmetry, the overlapping zone goes on increasing and hence results in the formation of hot and compressed zone with the decrease in asymmetry of the reaction. On the other hand, at the saturation time, the scenario of time evolution of collision is quite opposite. It means that highly asymmetric systems saturates at higher densities as compared to nearly symmetric systems. As discussed earlier, that system becomes hot and compressed with the decrease in asymmetry leading to more unstability of system and saturates at lower densities as compare asymmetric systems.

3.5 Time evolution of Multiplicity

In the present study, we use hard and soft equation of the state with free nucleon-nucleon cross section.

In the fig 3.3, we display the time evolution of final multiplicities of fragments at various scaled impact parameters ($\hat{b}$ = b/b$_{max}$). Here we have displayed the multiplicity of free nucleons (A=1), LMF's (2≤A≤4) and IMF's (5≤A≤35) for the reaction of $^{197}Au_{79}$+$^{12}C_6$ at energy 600MeV/nucleon for both Hard and soft equation of state.

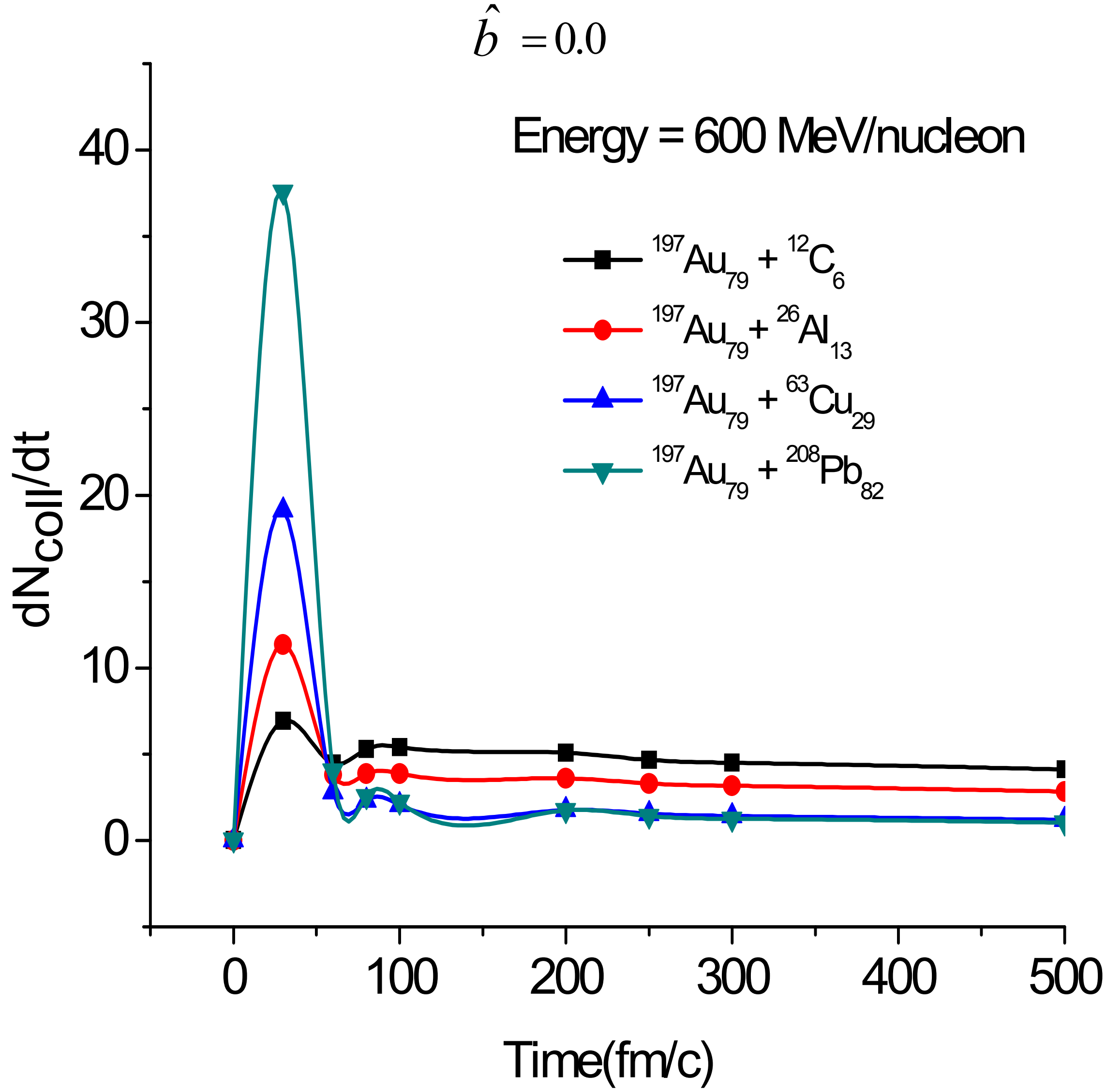

Fig: 3.2. Time evolution of allowed collision

It is observed here that multiplicity of LMF's saturates at 200fm/c, but shows a decay in case of IMF's after approaching a peak. However for free nucleons it is increasing continuously. This increase is due to the fact that instability of IMF's, MMF's and HMF's which become stable after decaying into fragments further and emits more free nucleons. In other words one can say that there is no rise and fall in case of free nucleons and LMF's, but for IMF's there is rise and fall.

Here we observed the multiplicity decreases on going from central to peripheral collisions. The multiplicity of LMF's is found to be more sensitive towards the equation of state as compared to the free nucleons and IMF's. The more number of LMF's are obtained with soft equation of state compared to hard soft equation of state. This is due to the different compressibility of soft (K=200MeV) and hard (K=380MeV) equations of state. In addition of compressibilities, symmetry energy also plays a very important role here. It is shown in literature that LMF's are more sensitive towards the symmetry energy. One can also use different clusterization methods to check the possible variations in the multiplicity of different fragments.

3.6 Rapidity Distribution

Rapidity is one of the important parameter in heavy ion collisions. Rapidity distribution is assumed to give information about the degree of thermalization and stopping achieved in the reaction [8,11]. The rapidity is defined as

$$Y(i) = \frac{1}{2}\ln\frac{E(i)+P_z(i)}{E(i)-P_z(i)}$$

where $E(i)$ and $P_z(i)$ are, respectively the total energy and longitudinal momentum of the i^{th} particle. In fig. 3.4, we have shown the rapidity spectra of $^{197}Au_{79}$+$^{12}C_6$, $^{197}Au_{79}$+$^{26}Al_{13}$, ^{197}Au+$^{63}Cu_{29}$ and $^{197}Au_{79}$+$^{208}Pb_{82}$ reactions for various $\hat{b}$ by using hard EOS.

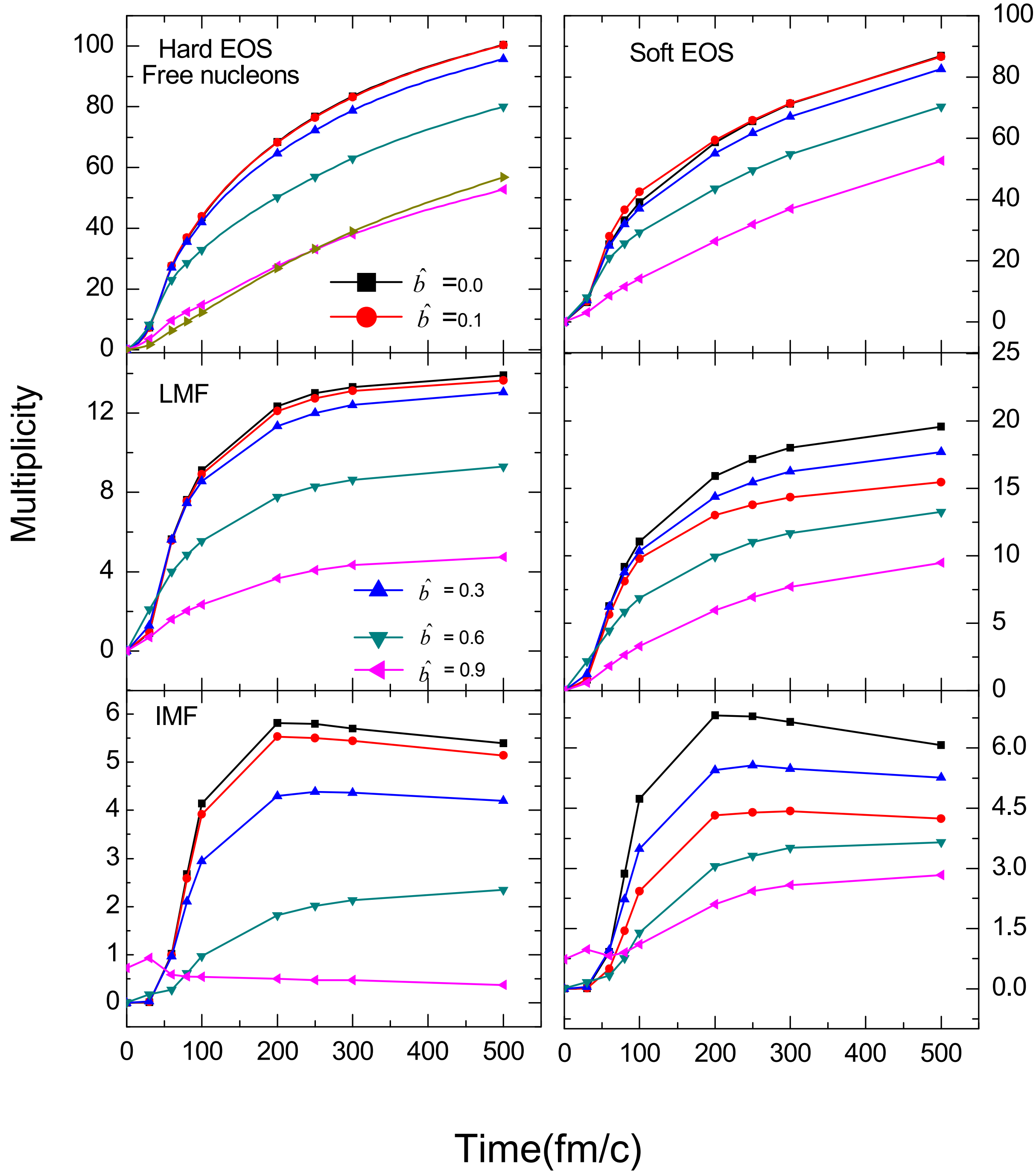

Fig: 3.3. Time Evolution of Multiplicity of Free nucleons, LMF's and IMF's

We would like to emphasize that distinct fragments species can be related to a single source in momentum space only for the central events ($\hat{b}$=0.0). Here all baryons are stopped and true multi fragmentation is observed. For the reaction ^{197}Au+^{208}Pb$_{82}$, single Gaussian is observed at central geometry indicating the production of IMF's from participant zone, on the other hand, with increase in the impact parameter, Gaussian starts to break-up into two peaks. This is indicating that with the impact parameter the thermalization of the system decreases and contribution of IMF's starts coming from the spectator zone. The two maxima of these curves directly reflect the finite impact parameters. As the mass asymmetry of the colliding nuclei increases, thermalization of the system decreases. One can see large peak of the projectile and small peak for the target. With increase in the asymmetry of reaction one can infer from the figure that IMF's are originated from the heavy projectile or in other words one can say that IMF's are created due to projectile fragmentation.

In ^{197}Au$_{79}$+^{12}C$_6$, the clear separation occurs at $\hat{b} = 0.9$. One can see that with increase in the impact parameter we observed the two bumps or two maxima peaks in all four reactions.

3.7 Mass and charge distribution

We have displayed the mass and charge distribution at three different impact parameters ($\hat{b} = 0.0, 0.3, 0.6$) for four reactions at energy 600 MeV/nucleon in figure 3.5 and 3.6 at saturation time 200fm/c. One can see here clear impact parameter dependence. At low impact parameters no heavy target remnant survives, as in case of ^{197}Au$_{79}$+^{208}Pb$_{82}$ system, as both target and projectile is of comparable size. The colliding nuclei is broken up into many pieces and none of them is greater than A=70. However the situation is different in case of large impact parameters and for lighter targets. Since in the semi peripheral collisions ($\hat{b} = 0.6$) are not violent enough to destroy the target completely. Here less than half of the projectile volume overlaps geometrically with the target.

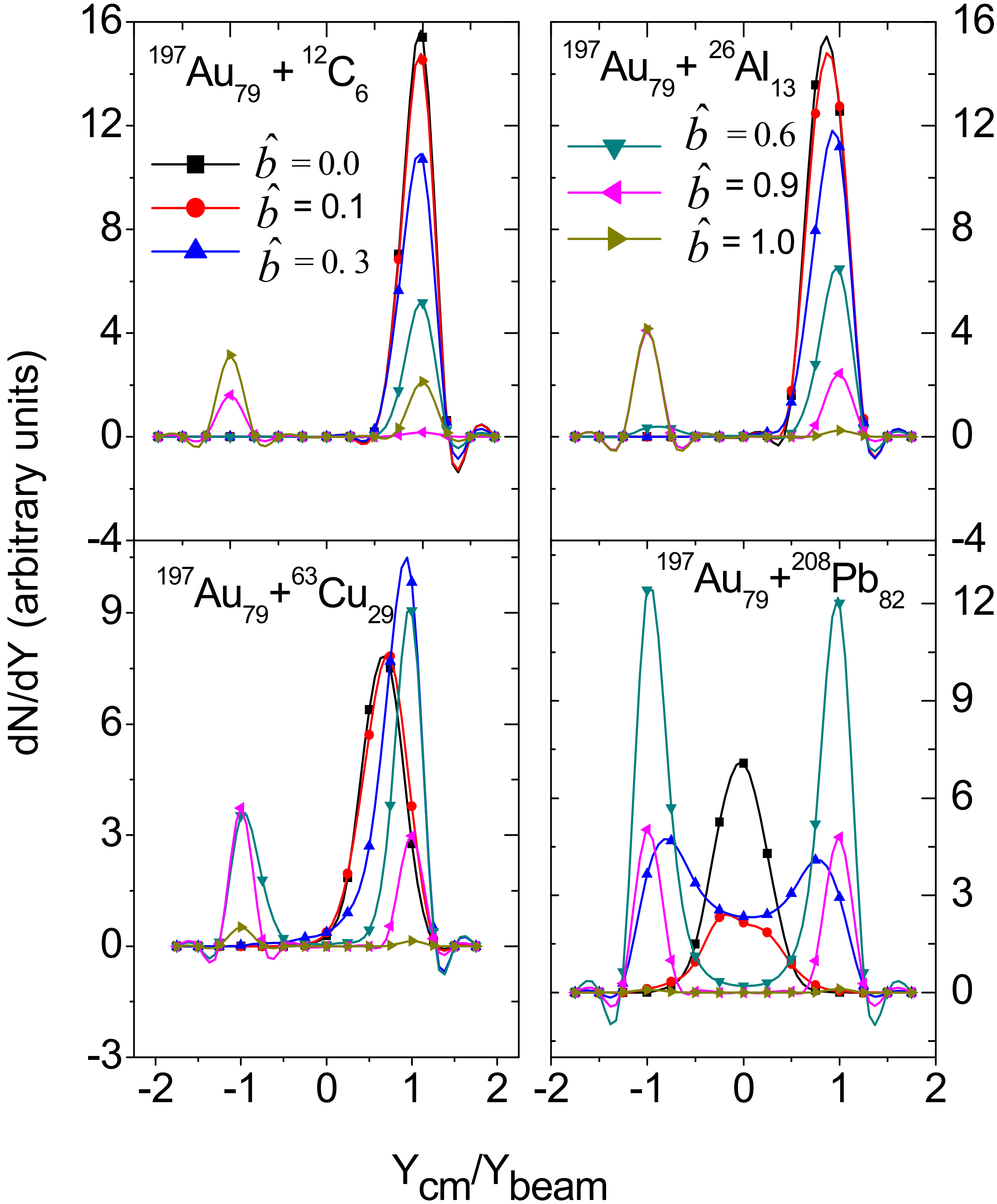

Fig: 3.4. Rapidity distribution of IMF's of four different reactions at various scaled impact parameters

We observe the projectile remnants A≥120 in case of $^{197}Au_{79}$+$^{12}C_6$ and $^{197}Au_{79}$+$^{26}Al_{13}$ systems and for other reactions it is relatively lighter.

At last we can conclude that as we increase the impact parameter spatial overlap decreases which results in the formation of heavy mass fragments in every reaction. The yield of heaviest cluster provides a tool to determine the impact parameter of the reaction [12-13].

Now in fig 3.6, the charge distribution for the same four reactions has been displayed. Here we observe a bump in $^{197}Au_{79}$+$^{12}C_6$ and $^{197}Au_{79}$+$^{26}Al_{13}$ reactions mainly at large impact parameters. This bump indicates that less amount of momentum is transferred for participant to spectator matter which leads to the emission of heavy fragments. However this is quite understandable as in central collision excitation energy deposited in the system is very large hence no heavy fragments is survived, but the case is opposite for peripheral collisions. So we can say that the heavy fragment formation is the main cause of this bump, as in case of mass distribution spectra. Similar conclusions have also been reported by several authors [14].

3.8 Multiplicity as a function of impact parameter

We have shown the multiplicity of free nucleons and LMF's as a function of scaled impact parameter $\hat{b} = b/b_{max}$ at 200fm/c for the reactions $^{197}Au_{79}$+$^{12}C_6$, $^{197}Au_{79}$+$^{26}Al_{13}$ and ^{197}Au+$^{63}Cu_{29}$ at energy 600MeV/nucleon. Here we observe the decline in multiplicity of free nucleons as well in case of LMF's. The reason behind this is that, on going from central to peripheral collisions, participant nucleons will decrease because overlapping is less and hence emit less number of nucleons and LMF's and we observe a fall in multiplicity.

Here we also observe a shift in multiplicity on going from reactions $^{197}Au_{79}$+$^{63}Cu_{29}$ to $^{197}Au_{79}$+$^{12}C_6$. This is because the mass symmetry decreases on going from $^{197}Au_{79}$+$^{63}Cu_{29}$ to $^{197}Au_{79}$+$^{12}C_6$, that's why more overlapping occurs in case of $^{197}Au_{79}$+$^{63}Cu_{29}$; consequently emit more nucleons followed by LMF's.

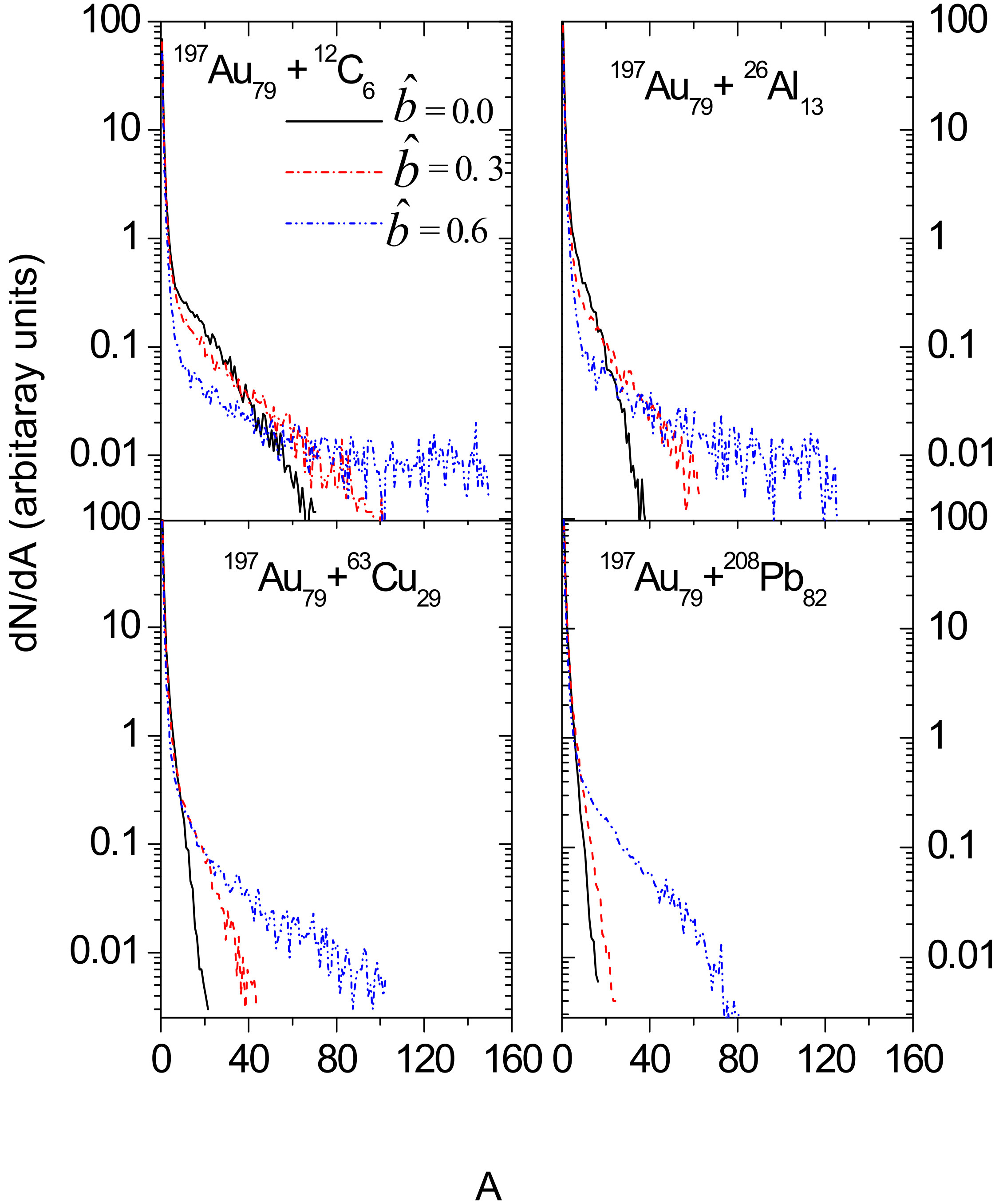

Fig: 3.5. Mass distribution of four different reactions

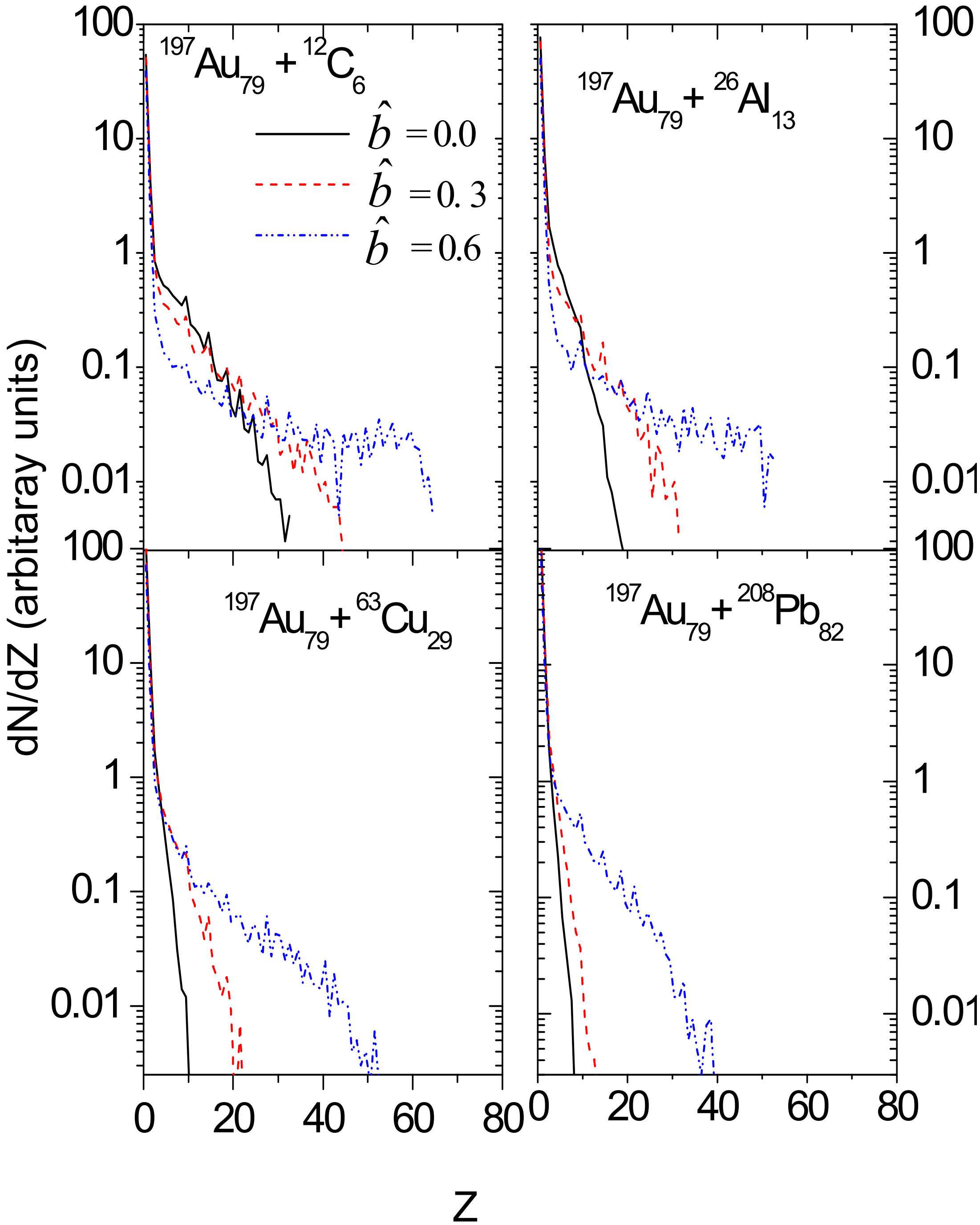

Fig: 3.6. Charge distribution of four different reactions

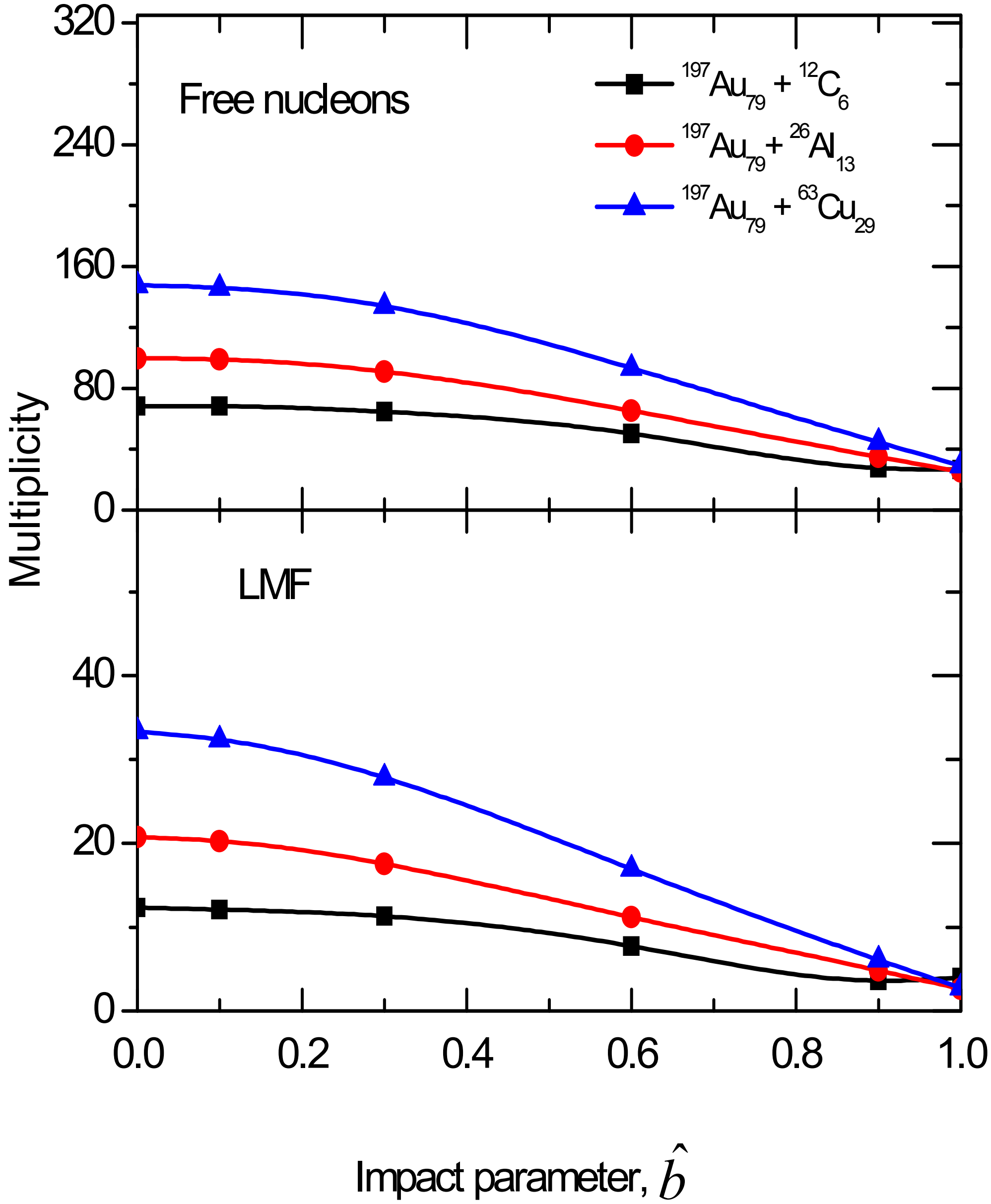

Fig: 3.7. Multiplicity of free nucleons and LMF's as a function of scaled impact parameter for different three reactions

3.9 Multiplicity as a function of system mass

In the figure 3.8 we display the multiplicity of free nucleons and LMF's as a function of the system mass at the different impact parameters for three ($^{197}Au_{79}$+$^{12}C_6$, $^{197}Au_{79}$+$^{26}Al_{13}$ and $^{197}Au_{79}$+$^{63}Cu_{29}$) different reactions. Both free nucleons and LMF's show increasing trends. With the increase in the size of system, number of the participant nucleons increases. This will lead to more thermalization of the system. Due to this reason, increase in multiplicity of those fragments will always be observed, which will originate from the participant zone. But on going towards the peripheral collisions, the amount of free nucleons and LMF's decreases as shown in the figure.

3.10 Dependence on projectile and target mass

The multiplicity of Intermediate mass fragments $\langle IMF\rangle$ and Z_{bound} correlation depends on the mass of projectile. The multiplicity of IMF as a function of Z_{bound} for targets Cu and Pb is displayed in fig (3.9). The quantity Z_{bound} is defined as sum of all atomic numbers Z_i of all projectile fragments with $Z_i \geq 2$.

We observe the target invariance of the $\langle M_{IMF}\rangle$ versus Z_{bound} correlation, which was first observed for the collision of gold projectiles on C, Al, Cu and Pb targets by ALADIN Collaboration [1-2]. Here we observe that multiplicity of IMF's shows a peak at semi central collisions. This is because in these collisions spectator part does not undergo collisions. In central and peripheral collisions few IMF's is observed. The reason behind this is due to the occurrence of frequent NN collisions in central collisions, whereas in peripheral collisions there, enough energy deposited from participant to spectator. In this way we get a rise and fall in multiplicity. This behavior is termed as rise and fall in fragment emission [7]. In the rise region, at large Z_{bound} the fragment production is governed by energy deposition whereas in fall region a limit of unconditional partitioning is approached [15].

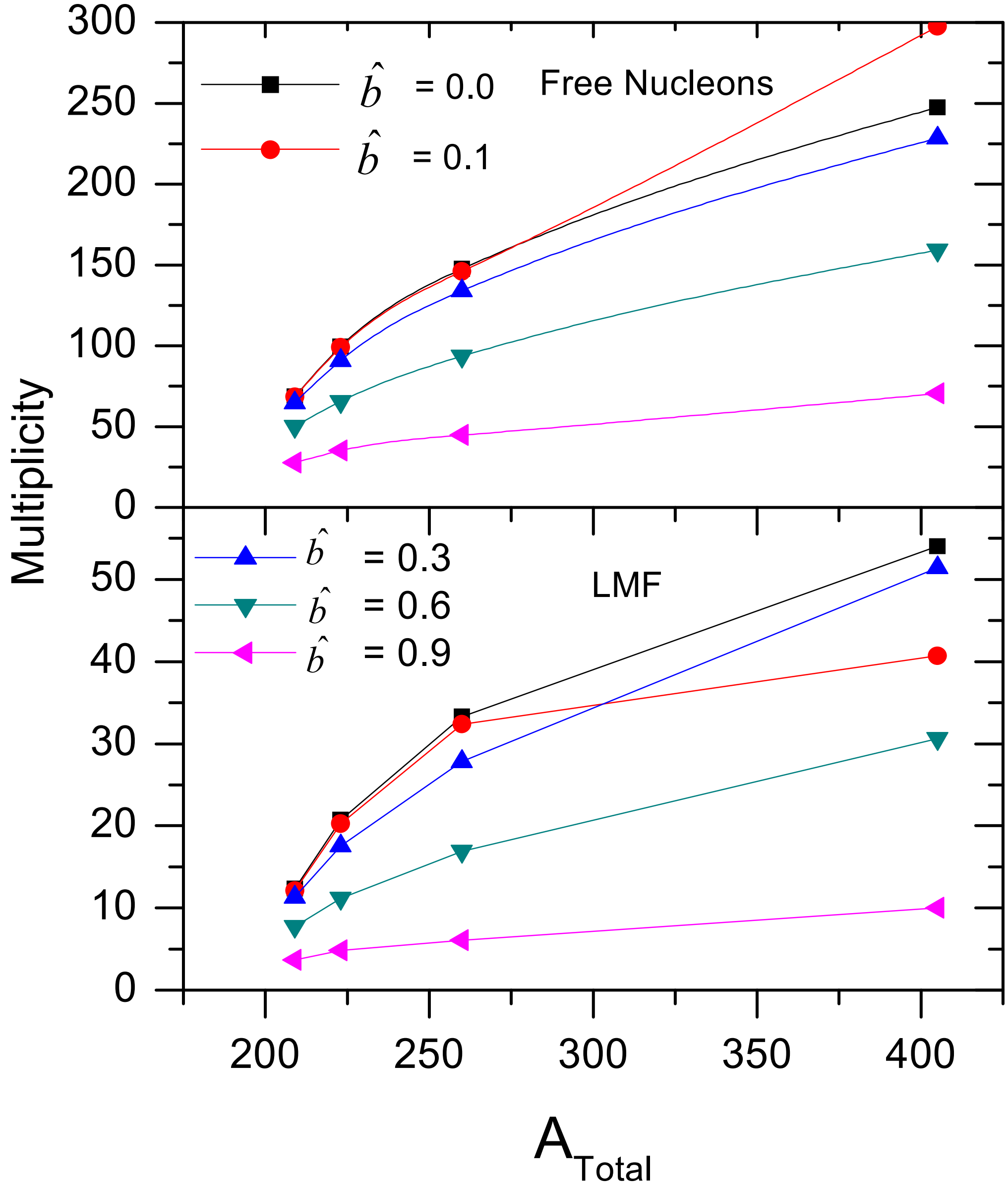

Fig: 3.8. Multiplicity of free nucleons and LMF's and as a function of system mass at different scaled impact parameters

We have carried out these theoretical calculations with the experimental data reported by ALADIN experiment [15] at energy 600 MeV/nucleon. It is observed that multiplicity shows a good agreement for low Z_{bound} or low impact parameters and heavy targets like Cu and Pb as shows in figure (3.9), but it fails for high Z_{bound} or impact parameters and for light targets like C and Al (not shown here) . This failure is due the method of analysis MST which we had used in our analysis, because MST method gives one heavy cluster at the time of high density. To overcome this failure one can explain the data nicely with theoretical predictions [16].

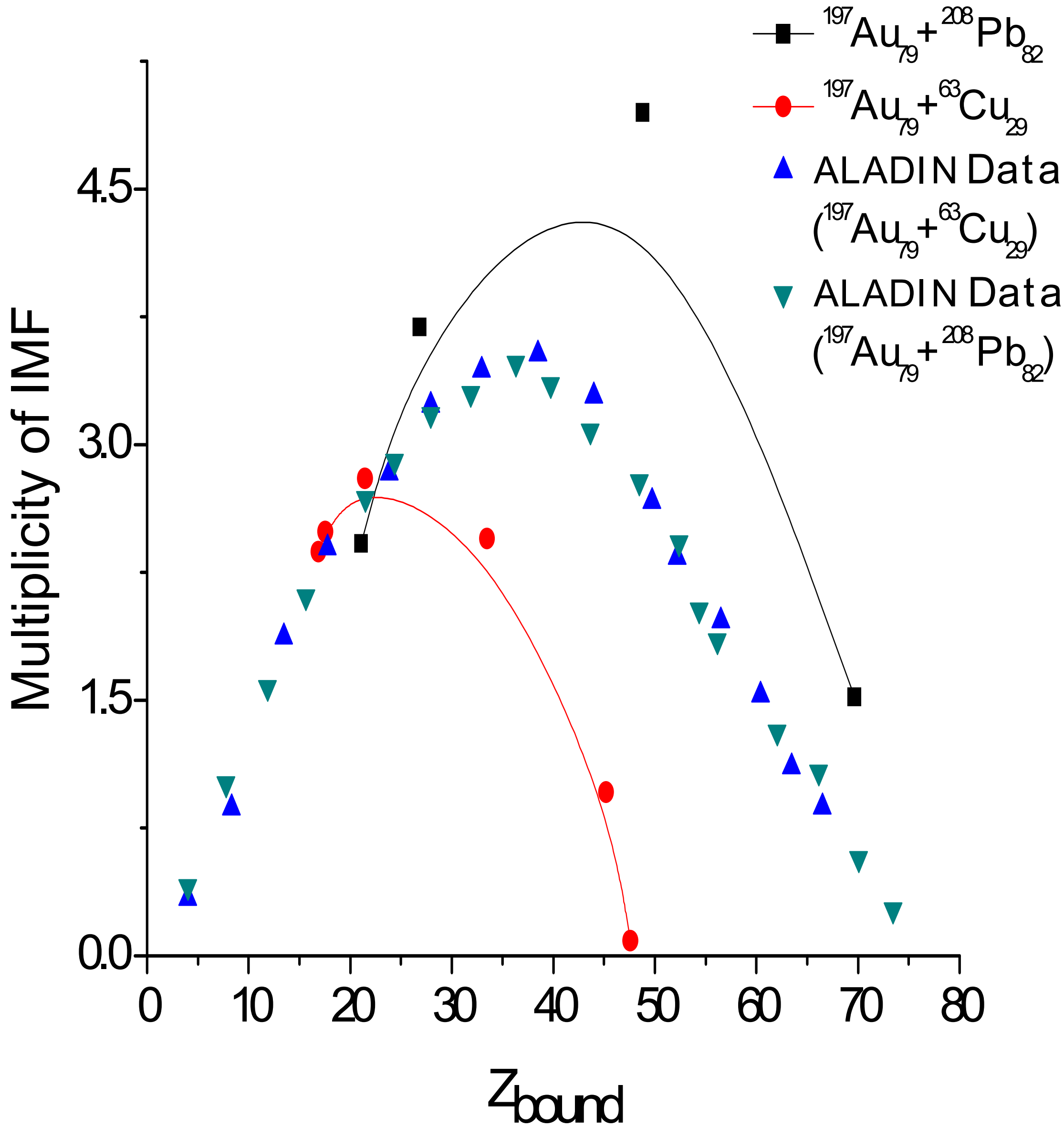

Fig: 3.9. Multiplicity of IMF's as a function of Z_{bound}

References

[1] M. Begemann-Blaich, V. Lindenstruth, , J. Pochodzalla, G. Raciti, G. Rudolf, H. Sann, A. Schuttauf, W. Seidel, W. Trautmann, A. Tucholski, J. Hubble, P. Kreutz, C. Adloff, P. Bouissou, G. Imme, I.Iori, G. J. kunde, S. Leray, Z. Liu, U. Lynen, R. J. Meijer, U. Milkau, A. Moroni, W. F. J. Muller, C. Ngo, C. A. Ogilvie, L. Stuttge, M. Schnittker, GSI preprint 98-15 (1998) and nucl-ex/9803007.

[2] A. Schuttauf et al., Nucl Phys **A 607** 457 (1996).

[3] S. Fritz, M. Begemann-Blaich, A. Moroni, W. F. J. Muller, L. Stuttge, M. G. J. kunde, M. Mahi, T. Odeh, V. Maddalena, A. Saija, U. Lynen, G. Verde, A. Moroni, J.Pochodzalla, G. Raciti, A. Worner, B. Zwieglinski, nucl-ex/9906001 (1999).

[4] W. Trautmann, nucl-ex/9611002, (1996).

[5] J. P Alard et al., Phys. Rev. Lett.**69**, 889(1992).

[6] Yevz Suhutz and TAPS Collaboration, Nucl. Phys. **A 599**, 97 (1996).

[7] C. A. Ogilvie et al., Phys. Rev. Lett. **67**, 1214 (1991).

[8] P. B. Gossiaux and J. Aichelin, Phys. Rev. **C 56**, 2109 (1997).

[9] N. T. B. Stone et al., Phys. Rev. Lett. **78**, 2084 (1997).

[10] R. K. Puri and S. Kumar Phys. Rev **C 57**, 2744 (1998), J. Singh, R. K. Puri, S.Kumar Phys. Rev **C 62**, 044617 (2000); ibid **65**, 024602 (2002).

[11] J. K. Dhawan, A. D. Sood, N. Dhiman, R. K. Puri, Phys. Rev **C 74,** 057901 (2006).

[12] G. Peilert, A. Rosenhauer, H. Stocker ,W. Greiner, A. Bohnet, J. Aichelin Phys. Rev. **C 37**, 2451 (1988).

[13] R. K. Puri, S. Kumar and J. Aichelin Phys. Rev **C 58,** 1618 (1998).

[14] S. Leray, C. Ngo, P. Bouissou, B. Remaud and F. Sebille, Nucl. Phys. **A 531**, 177 (1991).

[15] J. Hubble et al., Phys. Rev. **C 46**, R1577 (1992).

[16] R. K. Puri and Y. K. Vermani, Euro. Phys. Lett. **85**, 62001 (2009).

Chapter 4

Summary

This thesis contains the theoretical description about the target fragmentation in intermediate energy heavy ion collisions. So firstly we discuss about the heavy ion collisions and the experimental and theoretical scenario of multifragmentation in heavy ion collisions in the **chapter 1**.

The various theoretical models are given in **chapter 2**. We have discussed, in particular, the Isospin dependent *Quantum Molecular Dynamics (IQMD)* model used for the present study.

In **chapter 3**, we discuss the mass dependence or effect of target fragmentation of various quantities (like collision rate, fragment multiplicity etc.) by simulating the reactions $^{197}Au_{79}$+$^{12}C_{6}$, $^{197}Au_{79}$+$^{26}Al_{13}$, $^{197}Au_{79}$+$^{63}Cu_{29}$ and $^{197}Au_{79}$+$^{208}Pb_{82}$ at the energy 600MeV/nucleon and collision geometry is varied from central to peripheral. Our aim was to study the variation in the formation of fragments in asymmetric reactions. We simulate the reaction until 200fm/*c.* The phase space is analyzed by MST (Minimum Spanning Tree) method. The different kind of fragments like free nucleons, LMF's as well as IMF's are found to be sensitive with the asymmetry of the reaction. More heavy fragments are observed for the most asymmetric system, which will break into lighter fragments when one moves towards the symmetric systems. We observe rise and fall in the production of intermediate mass fragments with Z_{bound} (all atomic numbers Z_i of all projectile fragments with $Z_i \geq 2$). The results are in agreement at lower impact parameter, while large deviation is seen at higher impact parameter.